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*Published in:*  
Physics Procedia

*Publication date:*  
2015

*Document Version*  
Peer reviewed version

[Link back to DTU Orbit](#)

*Citation (APA):*  
González, A. G., Hemmsen, M. C., Wilhjelm, J. E., Jensen, H., Jensen, J. A., & Wilhjelm, J. E. (2015). Assessment of flatness of assumed planar surfaces for ultrasound investigation of elastic surfaces. *Physics Procedia*, 70C, 1233-1236.

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2015 International Congress on Ultrasonics, 2015 ICU Metz

## Assessment of flatness of assumed planar surfaces for ultrasound investigation of elastic surfaces.

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### Abstract

This study investigate the planarity of an assumed planar surface made of an elasomer fixed on its perimeter by a square acrylic frame. The central part of this surface is insonified with two different linear array transducers (types 8811 and 8670, BK Medical), yielding 11 images forming two 3D data sets. The change in flatness of the surface was determined by cross-correlation of the matrix of received signals. The cross-correlation was calculated between signals from the same image and as well as between signals that belonged to different images. The maximal change over the entire surface investigated is found to be in the order of a wavelength at about 12 MHz ( $\lambda=120\mu\text{m}$ ). Specifically, the surface showed weak concave bending for the two different transducers. The data was validated using the cross-correlation coefficient function. This yielded values of  $0.99\pm 0.01$  (mean $\pm$  std) when the algorithm was applied to scan-lines in the same image plane and  $0.93\pm 0.05$  when it was applied to scanlines in different image planes.

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Peer-review under responsibility of the Scientific Committee of 2015 ICU Metz.

**Keywords:** Planar; Surface; Clinical

### 1. Introduction

One of the challenges in experimental investigation of the behavior of the electrically received signal from a given transducer due to smooth and rough interfaces is that the measurement conditions must be very precisely controlled. Those measurement conditions include translation, angle, target geometry, etc. For the purpose of investigating the received signals from planar interfaces, we have in, our laboratory produced a number of planar surface phantoms by use of an elastomer Wilhjelm et al. (2001). This material was used to mimic human tissue and to ensure that the acoustic operation was conducted in the linear range. However, since the material is elastic and soft one cannot be sure that the surface is completely planar. This is investigated in this study.

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## 2. Materials and methods

**Equipment:** The experimental system consists of a clinical ultrasound scanner (type ProFocus 2202, BK Medical, Herlev, Denmark), and a linear array transducer (types 8811 or 8670, BK Medical). These two transducers have 128 and 192 elements and operates at 8 MHz and 9 MHz, respectively. The ultrasound scanner is connected to a computer that receives the beamformed RF data from the research interface Norholm et al. (2011), Hemmsen et al. (2012). The transducer was fixed to the moving part of a 3D translation system Norholm et al. (2011). This translation system was placed over a scanning tank. The tank was filled with demineralized degassed water. An ultrasound damping material was placed at the wall of the scanning tank behind and at the sides of the reflector phantom to minimize undesired reflections.

**Smooth surface phantom:** One smooth surface phantom produced by an elastomer (Biresin type U1202, by Sika Chemie GMBH, Stuttgart, Germany) was used as target. This material has acoustic properties similar to those of human soft tissues. It was moulded inside an acrylic frame placed on a glass plate which assured a perfectly planar surface during moulding. The smooth surface phantom is shown in Fig. 1.

**Transducer Settings:** For both transducers, 6 MHz and 12 MHz operation are exploited. The focal depth in the image plane of the transducers was set at 3 cm.

**Gantry setup:** The reflector phantom was mounted to a gantry aligned with the transducer. The transducer was mounted in a holder fixed to the manipulation arm of the XYZ translation system. The recorded signal at a new transducer measurement position was only used when it was ensured that the minute vibrations that occurred due to each translation step had died out by verifying that consecutive received signals did not change.

**Manual alignment:** The acoustic axis of the transducer (i.e. the normal to the transducer surface) was adjusted to be aligned with the x-axis of the translation system. The surface of the reflector phantom was adjusted to 0 degrees for both rotational axes and the normal to the surface was adjusted to be parallel with the acoustic axis of the transducer.

**Measurement:** Eleven horizontal images ( $M = 11$ ) were recorded at focal distance spaced  $Z_m = 7.5$  mm in the vertical direction (z-dir in this study, not to be confused with the beam axis). This ensured negligible correlation between neighboring images. To ensure that the majority of the acoustic energy was reflected from the surface of the elastomer and not the acrylic frame, the scan lines (dotted lines in Fig. 2) did only cover the inner part of the surface, as depicted in Fig. 2. The dotted lines indicates the image planes seen from the transducer. Specifically, the area covered is shown by the red shading (for transducer 8811) and the blue shading (for 8670 and 8811), the grey shading represents the whole phantom surface ( $10 \times 10$  cm).



Fig. 1. Planar surface phantom consisting of an elastomer ( $10 \times 10 \times 1$  cm) surrounded by an acrylic frame.

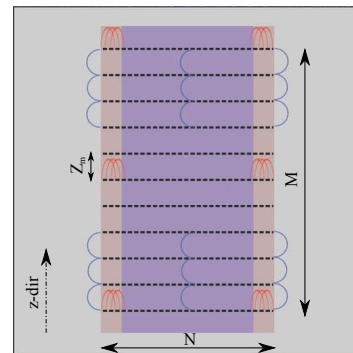


Fig. 2. Illustration on how the cross-correlation was calculated.

### 3. Signal Processing

**Windowing of the data:** To isolate the reflected signal between the front surface of the reflector phantom and water, a rectangular window was applied to each received beamformed signal. The window length was determined by extracting the estimated width of the pulse around the focal depth. By visual inspection, it was assured that no relevant data was windowed out. After windowing, the received signal for the  $m$ th vertical position on the surface of the reflector phantom, at focal distance from the surface, is denoted  $g_r(t; n, m)$ , where  $t$  is discrete time,  $n$  is the scan line number in the image (varies between transducers) and  $m \in [1; M]$  is the vertical position of the transducer.

**Cross-correlation:** Assessment of the flatness of the surface was performed by the cross-correlation of the windowed beam-formed RF data from the recorded scan lines. An example of two RF signals and their cross-correlation coefficient function can be seen in Fig. 3. Two different signal shift measurements have been studied on the windowed signals:

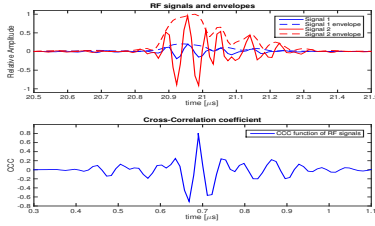


Fig. 3. Top: Example of two RF signals and their corresponding envelopes. Bottom: Cross-correlation coefficient function for the signals.

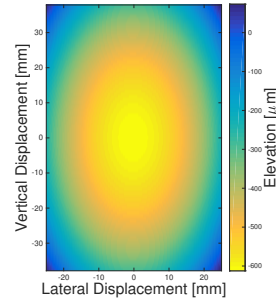


Fig. 4. Height profile of method validation.

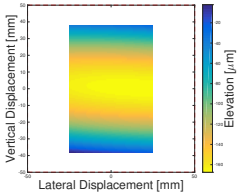


Fig. 5. Height profile of smooth planar surface measured with transducer 8811 at 12MHz ( $\lambda = 120.8\mu\text{m}$ ).

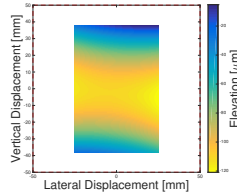


Fig. 6. Height profile of smooth planar surface measured with transducer 8811 at 6MHz ( $\lambda = 241\mu\text{m}$ ).

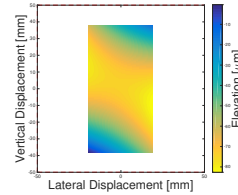


Fig. 7. Height profile of smooth planar surface measured with transducer 8670 at 12MHz ( $\lambda = 120.8\mu\text{m}$ ).

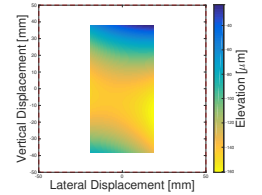


Fig. 8. Height profile of smooth planar surface measured with transducer 8670 at 6MHz ( $\lambda = 241\mu\text{m}$ ).

1) The shift between signals in the same vertical position  $m$  and different lateral position  $n$  (*within an image*) is studied as shown by the red arcs in Fig. 2. Specifically, the cross-correlation between each scan-line and its lateral neighbor is calculated for all scan-lines recorded at the same vertical position. The resulting shift is then stored as a matrix.

2) The shift between signals in the same lateral position  $n$  and different vertical position  $m$  is studied as exemplified by a few blue arcs in Fig. 2. Specifically, the cross-correlation between each scanline and its vertical neighbor (*image to image*) is calculated for all scan-lines recorded at the same lateral position. The resulting shift is then stored as a matrix.

It is to be noted that the resulting matrix has a size of  $(N - 1) \times (M - 1)$  due to the permutations that are possible. The cross-correlation measurements were validated by inspecting the associated cross-correlation coefficient, mean  $\rho$ . A robust method is expected to produce a  $\rho$  close to unity with small standard deviation.

**Flatness assesment:** The cross-correlation shift was stored in two different matrices, one for each calculation. The values of the shift are calculated between each scan-line and its neighbors, thus representing a gradient matrix. If

the surface is perfectly flat both matrices should be zero. In order to get a height profile of the surface, the gradient-matrices elements were added starting from the center of the surface and outwards. Afterwards, the zero shift point was assigned to largest value of the rows proximal to the acrylic frame. To finish, the resulting surface was fitted to the nearest quadratic surface to remove artifacts (outliers) and depict more clearly the geometrical nature of the surface. This method was validated creating two gradient matrices with fixed equal values. This should result in a height profile with a zero in the corners and decreasing values towards the center with a quadratic behavior as shown in Fig. 4.

#### 4. Results

Figures 5-8 show the 2D height profiles of the smooth planar surface, embedded in a white canvas that represents the total surface of the reflector, helping to identify the distance to the acrylic frame. All figures represent the same planar surface and it can be observed that: 1) the 2D profiles have roughly the same bending of the surface, but are more similar within a transducer than from transducer to transducer. 2) the surface is somewhat elevated in its upper right and lower left corners. 3) the surface bends in a concave manner. The maximal span over the entire surface is in the order of a half to one and a half wavelength.

The data was validated by means of the cross-correlation coefficient function. This yielded a value of  $0.99 \pm 0.01$  when the algorithm was applied to scan-lines in the same image plane and  $0.93 \pm 0.05$  when it was applied to scan-lines in different image planes.

#### 5. Discussion and Conclusion

Maximal shifts in the order of a wavelength over about 5 cm are observed from the results. This has the following implications: 1) As long as the diameter of the ultrasound beam (e.g. 90% of the intensity) at the surface is smaller than a few millimeters, the surface appears (locally) planar and the small curvature observed here should constitute a very small problem when investigations are conducted with focused transducers. 2) A change of  $150 \mu\text{m}$  over a distance of 5 cm yield a change in angle of the normal to the surface of 0.17 degrees. 3) When processing and analyzing data from many scan lines distributed over the entire surface, it could be important to take the bending into account when considering very distant scan lines or when very accurate measurements are needed Oh et al. (1994).

It should be noted that when not in use, the smooth surface is stored face down towards a glass plate, in order to maintain a planar surface as well as possible. This study used ultrasound for assessing one of the components of the measurement system. Other measurement approaches could be used, e.g. laser profilometry, but it is quite important that the assessment of the flatness takes place the same way as the phantom is actually used due to the fact that it is made of soft material.

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